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Fuzzy Reasoned Waypoint Controller for Automatic Ship Guidance

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Abstract: Guidance systems usually calculate the ship's desired course based on given waypoints or trajectory. In this paper, a fuzzy reasoned waypoint controller is discussed. The control laws considered here is similar to collision avoidance rules. However, instead of collision risk, nearness is reasoned by the fuzzy controller based on human operator's manipulating experience. Depending on the nearness of next and second next waypoint one at a time, fuzzy controller decides the desired heading. By this way, the necessity of calculating the circle of acceptance radius or path curvature separately at each turning point is eliminated. After getting the desired heading, as a course keeping controller, PD is used to correct the instantaneous heading. The proposed controller simplifies the total control design process and easily applicable to practical navigation path planning. Simulations with different sets of waypoints are carried out to justify the effectiveness of the proposed controller. Several experiment results are also included in this paper which validates the proposed control algorithm.

Keywords: Waypoint Control, Fuzzy Logic, PD Control, Navigation System, Guidance of Ship, Ship Control, MMG model, Free Running Experiment.

1. INTRODUCTION

Navigational path planning is a usual task of ship operators which is done based on the given set points called waypoints (WPs) to be passed. These waypoints are generated according to sail plan and weather data or given manually as autopilot inputs. Nowadays, the autonomous navigation of marine vehicles is gaining everybody's attention due to the inherent difficulties in manual ship navigation and control. Each ship's response is different from others and to get used to it, every ship operator needs some time. Therefore, to follow a planned path manually, i.e. proper timing of rudder angle changes as well as to take the counter rudder to overshoot the existing sway velocity and yaw rate has always been a crucial matter. As a result, in the field of ship manoeuvring, the waypoint tracking problem is an issue of high interest.

The waypoint tracking control problem is basically how making the ship follow a given set of waypoints by controlling the rudder (Fossen, 1994 and Petterson, 2001). To solve the problem, defining proper guidance algorithm is very important. There are several guidance algorithms exist (Jensen, 2011), like pure pursuit guidance algorithm, Line-of-sight (LOS) guidance algorithms, etc. Pure pursuit algorithm only considers the target i.e. waypoint and the vehicle itself. It seems like a predator use to chase a prey where the approach results in a tale chase. On the other hand, LOS guidance requires defining the enclosure radius or look ahead distance to get the LOS setpoint. However, in both cases WP switching algorithm is needed. On contradictory, this paper proposes a fuzzy controller based guidance algorithm which measures the nearness of next and second next waypoint one at a time and decides the desired course. Therefore, there is no need of additional algorithms for waypoint switching. In order to measure the nearness of WPs, distance to closest point approach (DCPA) and time to closest point approach (TCPA) are used, which are discussed in the later part of this paper.

Several researches are also done using Fuzzy logic for autonomous navigation, but in a different a way than explained in this paper. Cheng and Yi (2006) used fuzzy rules to get the rudder output directly based on the cross track error (the shortest distance between the ship and straight line joining two consecutive waypoints) and heading error. The authors also used fuzzy turning control to decide the turning starting distance at each waypoint. Lee *et al.* (2004) used fuzzy logic to decide the weight factor for goal (waypoint) that attracts the ship and obstacle that repels it. The authors' basic concept was based on Virtual Force Field (VFF) method.

In this paper, as mentioned earlier, using the value of DCPA and TCPA, the nearness of WPs is reasoned by fuzzy controller and desired course is calculated. Then, as a course keeping controller, PD is used to match the desired heading. Therefore, basically the proposed controller has two control loops. The outer loop belongs to the fuzzy controller that generates the desired course based on given waypoints for the inner control loop and the inner control loop makes the ship move towards the direction of minimising the heading error by controlling the rudder angle. The outer loop, i.e. the tracking control loop is treated as an additional feedback loop around the inner loop i.e. course keeping loop. For the outer control loop, the control laws similar to collision avoidance rules as mentioned by Hasegawa (1986, 1990 and 1993) are used. The author in his papers, measures the collision risk (CR) value depending on the existing marine traffic for the own ship using DCPA and TCPA. The basic control law is when the own ship approaches closer to any target ship, the value of CR will increase. Depending on such calculated CR value, necessary actions like changing of rudder, speed decreases etc. are taken. In case of waypoint controller, similar to this, as the ship is away from the second next waypoint, the command course will consider only for the next waypoint. However, with the increase of nearness to the next waypoint, the course will modify by considering both next and second next waypoint.

This paper is organised as follows. In section 2, a brief description of mathematical model used to predict the ship dynamics is presented. Section 3, describes the controller design and control scheme. Simulation results illustrating the effectives of proposed controller are presented in section 4 which is followed by some experiment results in section 5. At last, conclusions are given in section 6.

2. SUBJECT SHIP AND MATHEMATICAL MODEL

A considerable number of vessels travelling all over the world are only equipped with a single rudder and a single screw propeller. In this research, among those types of subject ships available, 'Esso Osaka' 3-m model is chosen which is scaled as 1:108.33. The main reason of choosing this model is the availability of large amounts of captive model test results as well as a physical model itself. Its details are given in Table 1.

Table 1. Principal particulars and parameters of model ship

Hull		Propeller		Rudder	
L (m)	3	D_p (m)	0.084	b (m)	0.083
B (m)	0.48	P (m)	0.06	h (m)	0.1279
D (m)	0.2	Pitch Ratio	0.7151	A_R (m^2)	0.0106
C_b	0.831	Z	5	Λ	1.539

The coordinate system used to formulate the equation of motion together with the wind direction consideration is shown in Fig. 1. Here, the ship heading is assumed as clockwise and wind direction as anti-clock wise positive.

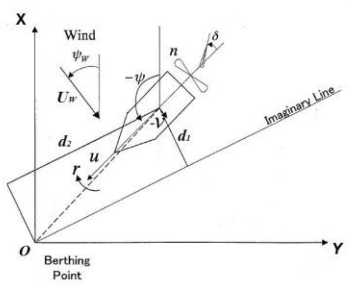

Fig. 1. Coordinate system

A modified version of mathematical model based on MMG (23rd ITTC meeting) for describing the ship hydrodynamics in three degrees of freedom is used for this model ship. In the MMG model, not only hull, propeller and rudder forces are considered separately, but their interactions are also taken into account. The corresponding equations of motions at CG (centre of gravity) of the ship are expressed in the following form:

$$
\begin{aligned}
(m+m_x)\dot{u}-(m+m_y)vr &= X_H+X_P+X_R+X_W \\
(m+m_y)\dot{v}+(m+m_x)ur &= Y_H+Y_P+Y_R+Y_W \\
(I_{ZZ}+J_{ZZ})\dot{r} &= N_H+N_P+N_R+N_W
\end{aligned}
\tag{1}
$$

X_H, Y_H, N_H: Hydrodynamic forces and moment acting on hull
X_P, Y_P, N_P: Hydrodynamic forces and moment due to propeller
X_R, Y_R, N_R: Hydrodynamic forces and moment due to rudder
X_W, Y_W, N_W: Hydrodynamic forces and moment due to wind

To consider the wind disturbances, Fujiwara wind model (1998) is adopted and instead of steady wind, gust wind is considered (Davenport, 1967).

3. CONTROLLER DESIGN AND CONTROL SCHEME

Fuzzy control is a practical alternative solution of variety of challenging nonlinear control problems. Optimal control laws can be implemented based on ship operator's knowledge while designing the fuzzy controller. Therefore, it can behave similar to that operated by human beings. In this research, fuzzy controller is used to decide the course for navigation path planning. Based on the ship operator's manipulating experience, the control rules for desired course are developed.

As mentioned earlier, the navigational path is consists of several set points named waypoints (WPs). These waypoints are usually selected at the turning points. Then, the path is planned normally directing to the next point (WP) to be passed. However, near the turning point, the fuzzy system will decide to choose the appropriate course defined by the next two WPs as following equation:

$$\psi_I = \psi_1 + (\psi_2 - \psi_1) * CDH \tag{2}$$

where, ψ_I is order of course change, ψ_1 is course of the shortest path to the next WP, ψ_2 is course of the shortest path to the second next WP and CDH is the reference degree to the second next WP ($0 \le CDH \le 1$), calculated by fuzzy controller.

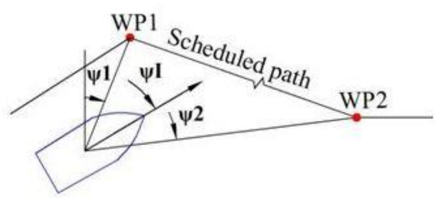

Fig. 2. Course command near a course changing point

Fig. 2 shows the course changing command near a course changing point (WP). In this research, to judge the nearness of the waypoint, TCPA (time to closest point of approach) and DCPA (distance of the closest point of approach) are used for fuzzy reasoning. Fig. 3 shows the bearing relationship between the ship and waypoint.

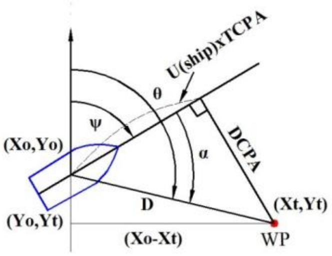

Fig. 3. Bearing relation between ship and waypoint

According to the figure, the distance between the ship and nearest waypoint is calculated as follows:

$$D = \sqrt{(Xo - Xt)^2 + (Yo - Yt)^2} \quad (3)$$

Then, the following calculations are done to get the bearing angle of waypoint from the ship.

$$\theta = a\tan 2\frac{(Yt - Yo)}{(Xt - Xo)} \quad (4)$$

$$\alpha = \theta - \psi \quad (5)$$

where, ψ is ship's heading, θ is encountering angle of way point from vertical axis and α is bearing angle of waypoint from the ship. Here, if the value of ψ , θ or α becomes negative, then 2π is added to make to them positive.

Finally, DCPA and TCPA are calculated using the following two equations.

$$DCPA = D|Sin\,\alpha| \quad (6)$$

$$TCPA = \frac{D\cos\alpha}{U_{ship}} \quad (7)$$

Another important point to be considered is the scale effect. There should be some difference on the nearness between a large ship and a small one. Therefore, the following equations are used for non-dimensionalised TCPA and DCPA. The nearness is then reasoned from $DCPA'$ and $TCPA'$ instead of $DCPA$ and $TCPA$ using the following two equations.

$$DCPA' = \frac{DCPA}{L} \quad (8)$$

$$TCPA' = TCPA\frac{U_{ship}}{L} \quad (9)$$

Membership function of $DCPA'$, $TCPA'$ and CDH are given in Fig. 4. The control rules to reason CDH is shown in Table 2, where the language valiables are defined as: SA=small, SM=small medium, ME=medium, ML=mediul large and LA=large. The rules considered here are similar to collision avoidance, i.e. "if DCPA is very short and TCPA is also very short, then CDH is very big". It means, if the ship is very far from second next waypoint, then the command course will consider only for the next waypoint. However, with the increase of nearness, the command course will modify by considering both next and second next waypoint. During the navigational path planning, the switching of waypoints is determined by TCPA value. Negative value of it for a particular waypoint ensures the ship already exceeded that point. Therefore, the controller considers the second next waypoint as next waypoint and third next waypoint as second next waypoint for further approach. The procedure continues till the ship reaches its second last waypoint.

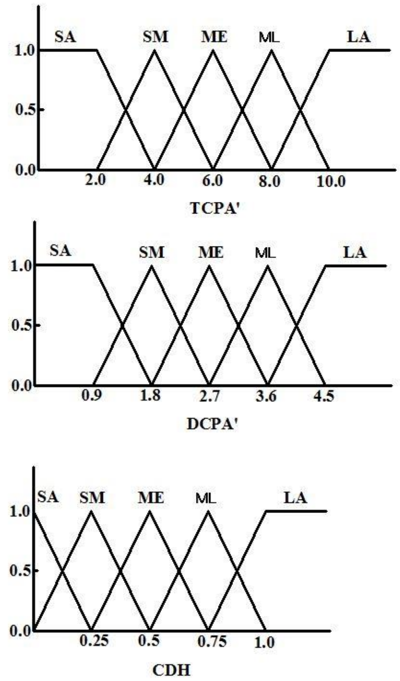

Fig. 4. Membership functions for course changing algorithm

Table 2. Control rules for course changing algorithm

		$TCPA'$				
		SA	SM	ME	ML	LA
$DCPA'$	SA	LA	ML	ME	SM	SA
	SM	ML	ME	SM	SA	SA
	ME	ME	SM	SA	SA	SA
	ML	SM	SA	SA	SA	SA
	LA	SA	SA	SA	SA	SA

After deciding the appropriate course by fuzzy reasoning, the course is corrected using a PD controller. The following equation shows the PD controller used here to correct the heading.

$$\delta_{order} = K_p(\psi_I - \psi) - K_d\dot{\psi}$$
$$\Rightarrow if \begin{cases} \delta_{order} \geq 25^0, \delta_{order} = 25^0 \\ \delta_{order} \leq -25^0, \delta_{order} = -25^0 \end{cases} \quad (10)$$

where, ψ_I is desired heading calculated by fuzzy reasoning, ψ is ship's current heading, $\dot{\psi}$ is the yaw rate, K_P is proportional gain and K_D is differential gain.

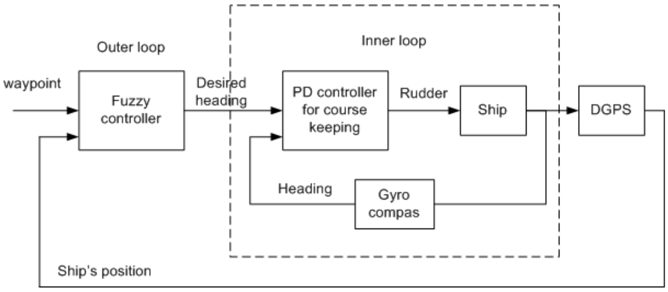

Fig. 5. Control scheme

Fig. 5 shows the control scheme of the proposed controller. For the outer loop, fuzzy controller is used to feed the desired heading to the inner loop after getting feedback of the ship's position. On the other hand, PD controller is used in the inner loop to keep that desired course. Therefore, the outer loop is treated as an addition feedback loop around the inner course keeping loop in this control scheme.

4. SIMULATION RESULTS

Using the proposed waypoint controller, simulations are done for different sets of waypoints. Gust wind from different directions is also tested to judge the effectiveness of the control under wind disturbances. The following figures illustrate such demonstration.

Fig. 6 shows the result for the set of waypoints that is placed at an angle -45º. Initially, considering the nearness of the waypoints, fuzzy reasoned desired course does not change much. Therefore, the command rudder is also zero.

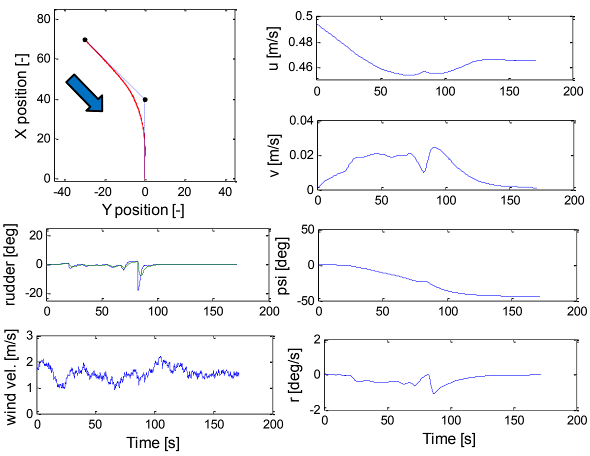

Fig. 6. Waypoints set at -45º, controller under wind of 1.5m/s from 45º

Soon after that, desired heading starts to change gradually and the PD controller decides to take rudder. The maximum nearness is judged by fuzzy controller after 80 sec and the PD takes comparatively larger rudder. Then, fuzzy reasons the desired heading for the next pair of waypoint i.e. 2nd and 3rd (imaginary point, not shown in figure) waypoints. In this case, the pair is set on the same line at -45º. Therefore, the ship finally merges with that line. The simulation is done under average gust wind of 1.5 m/s from 45º.

Fig. 7 shows the result for the set of waypoints that is placed at an angle 60º. Since the first waypoint has the same coordinate as mentioned in Fig. 6, initially the reasoned desired heading remains similar to initial heading. Then, depending on the nearness, the desired heading is modified and the PD controller corrects the course error under wind disturbances from 90º. Finally, the ship aligns with the line passes through the next pair of waypoints.

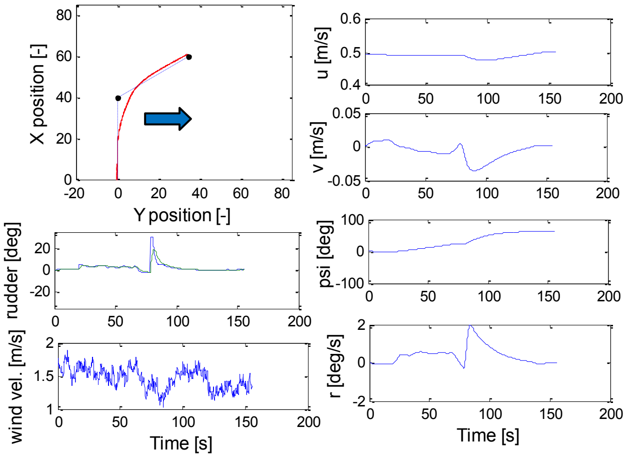

Fig. 7. Waypoints set at 60º, controller under wind of 1.5m/s from 90º

Fig. 8 shows the result for the set of waypoints that is placed to execute both starboard and port turn of the ship. Here, fuzzy reasons the desired heading and the PD controller decides the rudder command. The resulting trajectory seems quite satisfactory. The simulation is considered under wind of 1.5 m/s from 135º.

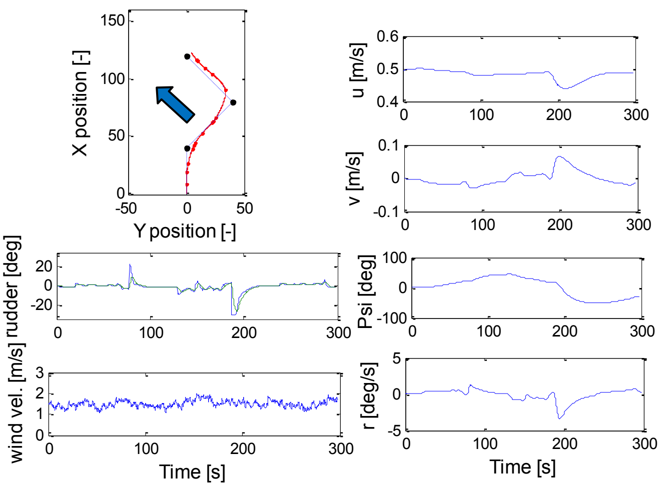

Fig. 8. Arbitrary set of waypoints, controller under wind of 1.5m/s from 225º

Waypoints are also set for 'S' letter shape and simulation is done to find out the ship trajectory using the proposed controller. Fig. 9 illustrates such result. Here, the simulation is done under wind of 1.5m/s from 0º. The result seems quite promising and the resulting trajectory almost matches with the set alphabet shape.

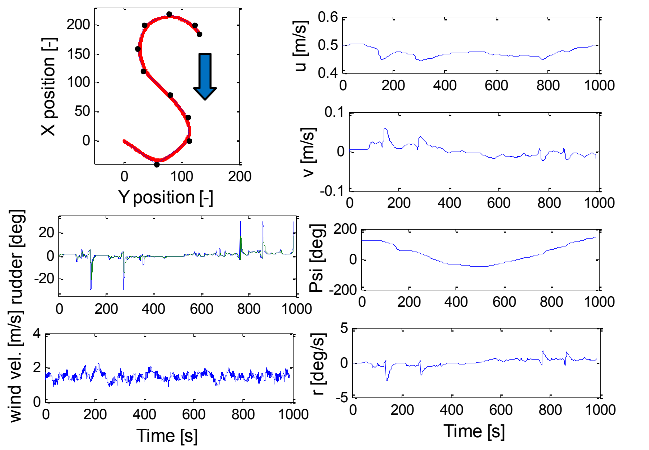

Fig. 9. Waypoints for S shape, controller under wind of 1.5m/s from 0º

Similar like above, several other simulations can be done to prove the effectiveness of the proposed controller.

5. EXPERIMENT RESULTS

After getting promising results in simulation works, experiments are planned and executed for different set of waypoints. To do such experiments, the free running experiment system is used for Esso Osaka 3-m model ship. To understand the total configuration of the free running experiment equipment system, Fig. 10 is given.

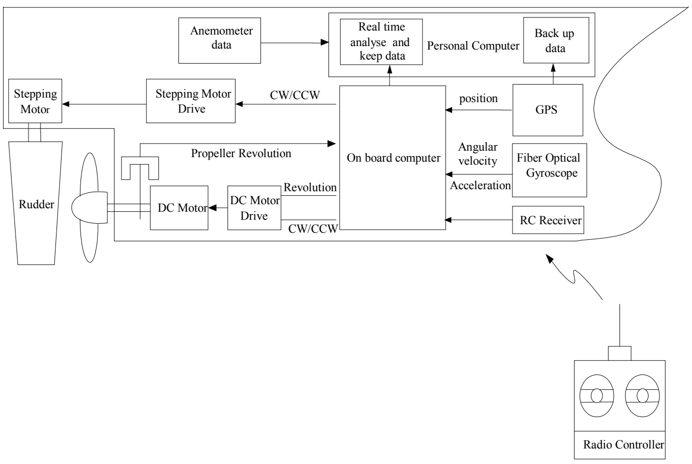

Fig. 10. Experiment equipments system

The experiments are carried out at inuki pond of Osaka University. Depending on the layout of the pond, different sets of waypoints are tested for the proposed controller. Such experiments are done for different initial headings to allow it to follow the given waypoints using the proposed controller. The sets of waypoints used for the experiments are given in Table 3.

Table 3. Set waypoints for experiments

Description	Waypoints (x, y)			
	I	II	III	IV
Fig. 11	-7.5, 10	-18.9, 36.2	-15.8, 53.8	-14.1, 65.8
Fig. 12	-8.4, 10	-21.7, 36.2	-18.6, 54.1	-16.7, 64.7
Fig. 13	-6.8, 15	-15.3, 38.2	-14.1, 44.8	-10, 54.8
Fig. 14	5, 10	10, 30	10, 50	5, 60

Fig. 11 and 12 show the results for ship, stating with heading 109.7º and 102.2º. Due to having larger course error with respect to 1st waypoint in Fig. 12, the controller took starboard rudder right at the beginning. On the other hand, the controller maintained comparatively small rudder in a straight like course up to 1st waypoint in case of Fig. 11. During the whole path navigation, the fuzzy controller measured the nearness of waypoints and the PD took the rudder for the desired course as determined by fuzzy controller.

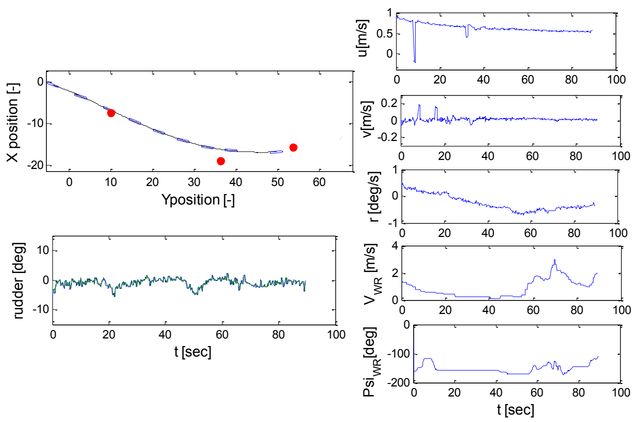

Fig. 11. Waypoint based navigation, initial heading 109.7°

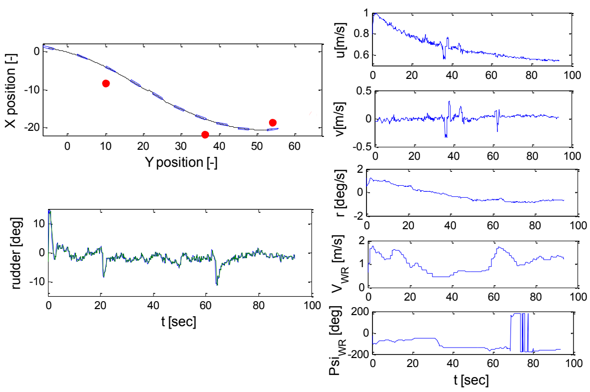

Fig. 12. Waypoint based navigation, initial heading 102.2°

The resulting trajectory and the command rudder are shown in the 1st column of these figures. The wind information during the experiments is shown in 4th and 5th row of 2nd column. Since the experiment field was too narrow and short for the larger inertia of the model ship, small gap exists while passing by the set waypoints in these experiments. However, such gaps could be minimised by proper selection of the waypoints. The output of the PD controller for the desired course in the above two experiments looks quite sensitive and rudder action is too frequent. Therefore, for further experiments, the coefficients for the PD controller are tuned to give less frequent movement which ensures smoother rudder for practical operation.

Fig. 13 and 14 show the results for other sets of waypoints using the tuned PD controller for the desired course. This time, waypoints for both on left and right side of the ship are tested. The results, unlike before, clearly show smoother rudder operation to maintain the desired course.

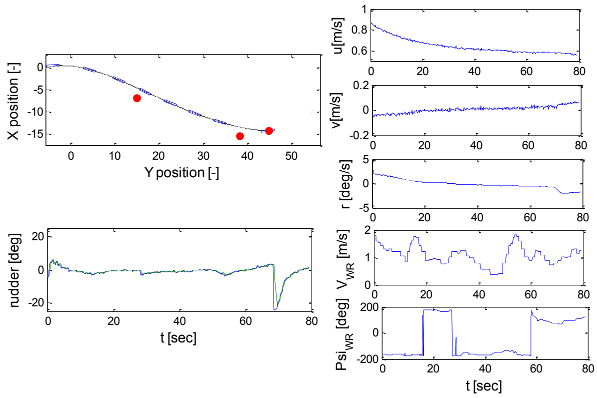

Fig. 13. Waypoint based navigation, initial heading 88.5°

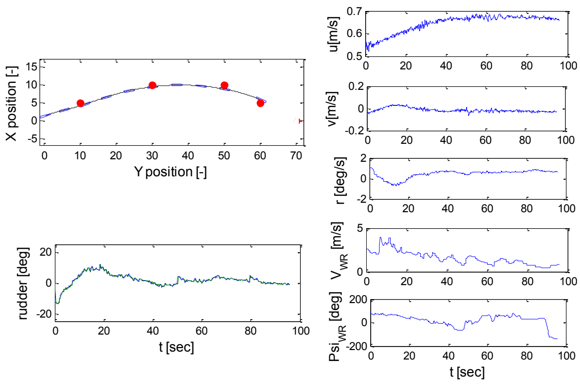

Fig. 14. Waypoint based navigation, initial heading 72.3°

Fig. 13 shows the result for the waypoints that are set on the right side of the ship. The experiment is done for ship starting with heading close to 90°. Therefore, like in Fig. 12, initially there exists a larger course and due to having a shorter path than expected for course correction, there exist small gaps while passing by the given set waypoints. On the other hand, Fig. 14 shows the result for the waypoints that are set on the left side of the ship. This time, the initial course error is not that much and higher propeller revolution is chosen than before. Finally, the ship almost passes through the given set points.

6. CONCLUSIONS

This paper presents a double loop feedback controller for waypoint navigation. The outer loop belongs to fuzzy controller that generates the desired course for a set of waypoints. This desired course is then fed to the inner course keeping loop for necessary course correction. The fuzzy controller is designed based on the human operator's manipulating experience. Based on the value of DCPA and TCPA, the nearness of the next waypoint is measured and the reference degree to the second next waypoint is modified by fuzzy controller. Therefore, based on the nearness of two consecutive waypoints, fuzzy controller gradually modifies the desired course. In the mean time, if the TCPA becomes negative for the next waypoint, for further navigation, second next waypoint becomes next and the third next becomes second next. This procedure continues for the rest of path navigation.

Using such control scheme, simulations are done for different sets of waypoints under gust wind disturbances. The results are quite promising. Model ship experiments are also done and included in this paper. Since the proposed control scheme simplifies the total control design process, full scale experiments are now planned and will be done within few months.

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